HAROLD F. BLUM

Time's Arrow and Evolution

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BY HAROLD F. BLUM

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To Mabel and Jannet

PREFACE

I FIRST began to think about possible relationships between the second law of thermodynamics and organic evolution during the summer of 1933 while a guest of the laboratory of the Collège de France, at Concarneau in Brittany. The previous spring I had discussed Henderson's *Fitness of the Environment* with my class in General Physiology at the University of California, and no doubt the seed was sown then in my mind. Shortly after my return home I presented some of my ideas at a meeting of geneticists. There was nothing to suggest that the audience found the concepts too radical, though perhaps the lack of response indicated that they were not worth the trouble of refuting. My paper was, however, duly reported by the press, and did cause a little stir. Numerous letters to the editor of one of the local papers acclaimed my having refuted Darwin. The letters became so numerous that the editor undertook to answer them, explaining—more clearly than I had—what I was really talking about, pointing out that nothing I had said denied evolution by natural selection. This incident has warned me against the possible misinterpretation of this book, and so I feel I should point out that, so far as I am aware, none of the ideas presented are in conflict, indeed they seem complementary to, the concepts of modern Darwinism.

Subsequently, the book made numerous false starts, and has suffered various delays. A great war has occurred, and there have been other vagaries of fortune to postpone its completion. In the intervening years many ideas have changed radically, particularly as regards cosmic evolution, so that much that was written only a few years ago does not hold today. This shift in point of view has emphasized the importance of putting the argument in a general form rather than tying it too securely to any particular theory. There has been nothing in all this change, however, to weaken the status of the second law of thermodynamics; rather its general applicability to the evolution of the nonliving world—and to that of the living world as well—has become more obvious.

Others have dealt with the relationship of the second law to organic evolution, both before and since my first essay into the field. At present, interest in the subject seems to be increasing, and many are concerned with the problem who have not put their thoughts in print.

This seems natural enough; for it is difficult to believe that the evolution of living things, a process that has proceeded unidirectionally in time, could be independent of the great principle of irreversibility. I have attempted in this book to examine various relationships between the second law of thermodynamics and organic evolution, and in so doing I may not in all cases have paid strict attention to the origin of the ideas involved. Hence it may seem that due concern has not been given to the writings of others, but by this time it would be impossible to untangle all the ideas and trace out their derivations. The least I can say is that I feel immeasurably in debt to those who have helped me to write this book. Many of these I have not known personally, our only contact being through what they have published. I have tried in my bibliography, at the end of the book, to include those references that have contributed importantly to my thinking in this regard, and also some that may assist the reader who wishes to explore farther into particular aspects. More specific citations have also been made in the footnotes.

A number of persons undertook to read the manuscript, or parts of it, in various stages of completion; and to offer criticisms which have been most valuable to me in making revision. It is a pleasure to acknowledge this kindness on the part of George W. Bain, John Tyler Bonner, A. F. Buddington, Marcel Florkin, Otto Glaser, David R. Goddard, Warren K. Green, H. H. Hess, Walter Kauzmann, Gordon M. Loos, Arthur K. Parpart, Newton L. Pierce, Harold H. Plough, and C. B. van Niel. My thanks are also due to Mrs. Dorothy D. Hollmann for her critical editorship of the manuscript, and to Mrs. Margie R. Matthews for preparation of drawings.

The book's final coming into being was made possible by a John Simon Guggenheim Memorial Foundation Fellowship which was granted for the purpose at the end of the war. And I must thank Mr. Henry Allen Moe for his kindly advice that I undertake the thing I really wanted most to do, rather than follow some more "practical" plan. Without this timely encouragement the work might have been postponed indefinitely.

I take this opportunity to thank my numerous hosts during the course of my Fellowship; the Departments of Physiology and Zoology at the University of California, the Department of Zoology of the University of California at Los Angeles, the Department of Biology at the University of Rochester, and the Marine Biological Laboratory at Woods Hole. Seminars which I gave before certain groups were helpful to me in crystalizing my ideas, and I am grateful for the comments I received at those times. The San Francisco Bay group known as the Biosystematists was one of these; the biology seminars at the

University of Rochester and at Harvard University were the others. I have completed the book while a member of the National Cancer Institute and of the Department of Biology of Princeton University—to both my grateful appreciation for their assistance and many courtesies. And I cannot end without again mentioning the place where it all began, among pleasant and stimulating surroundings at the Laboratoire de Zoologie Maritime, of the Collège de France, at Concarneau.

HAROLD F. BLUM

Woods Hole,
August 1950

PREFACE TO SECOND EDITION

IN MAKING the limited revision to which I am restricted at this time, I have the feeling that I am not doing full justice to the readers and reviewers who received the book so graciously when it appeared. They have been, on the whole, so kind in their comments that I do not like to let them down. A good many things have been learned in the meantime, and points of view have shifted in several fields, so that there is much new that could well be incorporated; but I have had to limit myself to those things that bear directly on the main argument. It has been borne home to me that in another three years many more revisions will be needed, for science moves rapidly these days; and this has, perhaps, kept me from taking as definite a stand as I might have in some places. But I have contented myself with the thought that in spite of the changes I have had to make, and the many more I could have made; the principal theme seems to stand without more than minor modification. The need to take the second law of thermodynamics into our thinking about evolution appears to me all the more certain; although I am less sure that I have said so as clearly as I could wish.

In presenting the argument in the first place, it seemed necessary that the reader should have a clear understanding, on at least an elementary level, of numerous aspects of the problem; and my attempt to provide this may have confused some readers as to my intention. It was perhaps unavoidable that a certain number of them should have found parts of the book too elementary, and other parts somewhat abstruse; since any specialist must find the handling of his own subject incomplete, while other fields, with which he is less familiar, may appear to him to be treated at a more advanced level.

That a good many readers have found something new in the book in the way of general approach is heartening; and if some have found

only an assembly of more or less general information, I think I should not complain. The latter may have reason on their side, but I am encouraged to remember that on first reading *The Fitness of the Environment* there seemed to me very little in it that was new. But even to make so slight a comparison of the two books is a form of self-flattery in which I should not, perhaps, indulge.

The greatest amount of revision has been called for in the parts dealing with the origin of the earth, and the origin of life. In the latter case, I have added a fairly extensive addendum to the chapter concerned. I should have liked to say more; but have decided to leave the reader ample room for his own speculations, after cautioning him to stay within the bounds of physical principles, including the restrictions of the second law, and of the geochemical and biological evidence. In order to avoid rearrangement of the index, this addendum has been inserted without changing the original pagination. I have also added a number of recent items to the bibliography; reference is made to certain of these in the revised text, by the authors name and the date.

I am happy of this opportunity to thank the Princeton University Press, and particularly Mr. Herbert S. Bailey, Jr., for the fine job of manufacture of the book, and for many kindnesses.

HAROLD F. BLUM

Princeton
December 1954

PREFACE TO THE THIRD EDITION

The years since this book was first written have been packed with more scientific activity than any comparable period in the world's history, and many additions and revisions would have to be made to bring this edition completely "up to date." Many of the pertinent developments—particularly in biochemistry dealing with intermediate metabolic pathways and with the genetic code—have been treated so thoroughly elsewhere that I have assumed them to be available to all readers in one form or another. Therefore I have tried to make only such changes as might make the volume compatible with this later knowledge, and have not attempted extensive review.

What has concerned me in revising is the increasing trend toward "deterministic" thinking that has come with our scientific successes, often bringing with it tacit teleology and panglossianism. Implications of Information Theory that might give a more "probabilitic"

view have had less influence. For example, analogies between computer operation and natural selection seem to have been generally neglected. I have, in an added chapter, pointed out some of these analogies, their bearing on the explanation of evolutionary processes, and the dangers of carrying analogy too far. Some of the things said in that chapter may seem to be repetitions from earlier ones, but I believe they can stand reemphasis.

A good many of the notions in the added chapter have been tossed about in pleasant conversations with Roger Pinkham, and I am not sure just what part is his and what mine, nor how much he would wish to take responsibility for. But I am happy to acknowledge my debt to him, and thank him for his criticism of the new chapter. I have also to thank Walter Kauzmann, Eugene McLaren, and Larry Mason for valuable criticisms of that chapter.

HAROLD F. BLUM

State University of New York
at Albany
March 1968

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TIME'S ARROW AND EVOLUTION

"Li tens qui s'en va nuit et jor,
Sans repos prendre et sans sejor—"
—WILLIAM OF LORRIS

I · PERSPECTIVES

"*Ah, but a man's reach should exceed his grasp.*"—ROBERT BROWNING

THE idea of evolution from a past primitive state to a present more complex one brings unity to biology, explaining the relationships among living organisms and the recurrent patterns one finds throughout the living world whether it be explored with binocular, test-tube, microscope, or Geiger-Müller counter. The concept is not unique to biology; the astronomer regards the universe in the same way, and the geologist, and others too, find evolution essential to the understanding of the broader aspects of their subjects.

The beginning of widespread influence of the evolutionary concept in biology is associated with the middle of the nineteenth century and the name of Charles Darwin. Earlier in that century the general idea of evolution was not uncommon in natural science, but an acceptable mechanism for explaining organic evolution had been wanting. The introduction of the idea of variation and natural selection by Darwin provided a rationalization, serving to crystallize what before had been a vague recognition of some sort of historical trend. The original Darwinian ideas underwent various modifications, but have survived as a part of our modern concept of evolution which has been given a firm basis by the science of genetics and the introduction of statistical treatment of populations. There are few biologists today—and the present author is certainly not one—who would venture to attack this solid structure.

One may ask, however, if all the aspects and implications of evolution can be satisfactorily explained on this basis alone. Any scientific approach to the problem requires that there be a mechanism which explains why evolution took the pathway it has instead of some other *possible* or *imaginary* pathway. Natural selection undeniably supplies such a mechanism, but is this necessarily the only one which permits such "choice" of pathway, and are not some of the apparent "choices" purely imaginary ones that can be ruled out on other grounds? The question might be put in another way: To what extent has the course

of evolution been determined by strictly physical factors that have permitted no exercise of natural selection, and to what extent have the former set the limits within which the latter might act? Can the two things be clearly separated, and what errors of interpretation may be made if we are unable to do so? These are among the questions that will be posed—I do not promise to answer them—in the following pages.

To make even a start in this direction, one needs to view evolution in its entirety—the history of the universe. As in human history, itself a part of evolution, each stage in evolutionary history has depended upon the stage that preceded it, and it is possible to err in interpretation if one studies isolated periods without due regard to the influence of earlier ones. Most works dealing with organic evolution focus attention on its strictly biological aspects, disregarding to a great extent those physical factors that have determined the basic pattern along which living systems could subsequently develop. To understand these factors and restrictions, one needs to go back to the origin of life, and beyond into the domains of terrestrial and cosmic evolution. This is shifting ground, dangerous for the tyro, and caution limits the biologist to a general survey from relatively safe vantage points which may be expected to survive any less than major cataclysms. Yet perhaps it is this limited and necessarily superficial kind of reconnaissance which may be most helpful in the interpretation of later evolutionary events. For the evolutionist may in his cursory exploration stress relationships which are of less importance to the specialist whose approach to those aspects immediately important to his own investigations is more reliable and exact. At least, such a rationalization gives me the temerity to undertake an exploration into the remote past; where I will be, more often than not, venturing beyond the limits of my proper discipline.

The suggestion that life processes are only interpretable in terms of their history will not startle the evolutionary biologist, although he may not be prepared to trace this idea as far back as is attempted here. The physicist or chemist may be less ready to admit this generalization, yet his failure to do so may lead him either to minimize the complexity of the problem of explaining life in physical and chemical terms, or to the opposite extreme which merges with mysticism. The need for taking into account this time dimension of living systems is one of the themes which recurs in the following pages. A good many of the properties of living organisms that appear unaccountable in terms of the inorganic world may stem from events which would be highly improbable within our modern frame of reference, but which, when we take into account the lavish amount of time for them to have

occurred in, become much less improbable. The same argument might apply to many properties of the non-living world as well. To appreciate the importance of time in the evolutionary process, one needs to grasp as well as he can the tremendous extent of it which stretches between us and the origin of our planet, and to gain an idea of the relative positions of evolutionary events therein. To orient the reader in this regard, Chapter II summarizes briefly the chronology of earth history and the basis of absolute measurement of evolutionary time. It is said there that life probably originated sometime between two and four billion years ago. But how is the exact moment to be determined?

Perhaps the only way would be to build a time machine—say, an improved and expanded version of that described by the late Mr. H. G. Wells—load it with a group of representative scientists: geneticists, physiologists, chemists, paleontologists, physicists, varieties of morphologists and systematists, or extend the list as you will, and in this happy company travel back at a tempered pace over the four billion years of the earth's history. This would surely be the proper way to reach an understanding of the course of evolution and to pick out the exact point at which life appeared on the planet. Or would it? Although the voyage would no doubt be an instructive one, I think the travelers should be prepared for wide divergence of their opinions, even with the panorama unfolding before them. Each would, I feel sure, be looking for life's origin through different glasses, his criteria depending largely upon the background of his approach to the problem. Conceivably, choices of the point of origin might differ by many millions of years. Not having the facilities at hand for the construction of the time machine my only recourse has been to the expressed opinions of colleagues from various fields; these and my own uncertainty have led me to the above prediction. So, although Chapter X will deal with some of the problems involved in the origin of life, no date and no definite sequence of events will be proposed.

Within our short span of life we are continually aware of the irrevocable passage of time—aware that the same events never exactly repeat themselves whether we wish or no. Viewed in perspective, evolution is characterized by the same one-wayness in time, occasional statements as to its reversibility notwithstanding. It would be useful to us, as evolutionists, if there were some measure of this one-wayness of events. Science offers only one widely general principle which seems applicable; the *second law of thermodynamics*. One way of stating this law is to say that all real processes tend to go toward a condition of greater probability. Sir Arthur Eddington showed insight into the bearing of this law upon our problem when he described it as "*time's*

arrow." This implies that the second law of thermodynamics points the direction of all real events in time, although giving no indication of the speed with which they happen. It should be tempting, then, to explore the relationship between time's arrow and organic evolution.

Few, if any, physical scientists would hesitate to apply the second law of thermodynamics to the evolution of the nonliving world; yet even here its applicability may be worth examining. For the second law is in a sense an empirical and pragmatic law which owes its acceptance to the fact that it has worked whenever it has been put to test. The second law can be tested by setting up a self-inclusive system, deducing the changes that should occur, and accurately measuring these changes to see if they agree with prediction. In a sense, we may be accused of rigging the data to obtain agreement, but the fact that we have never failed to obtain it encourages our belief that we deal with a universal principle. Before any claim of a failure of the second law of thermodynamics with regard to any aspect of the nonliving world could be taken seriously, there would have to be absolute assurance that the system involved had been properly set up for examination.

There have been numerous successful applications of the second law of thermodynamics to different aspects of living systems; these encourage the belief that this principle also applies there in a more general sense. Nevertheless, there are from time to time assertions that living organisms manage in some way to violate this principle. In such instances it does not appear that the system has been set up in such a way that it would be possible to reach the conclusion implied, but such statements are likely, because of their dramatic character, to have unwarranted influence on general thought. In Chapter VII living systems as a whole are treated as a thermodynamic system, and no basis is found for claims that the second law of thermodynamics is not obeyed. At other points in the book there will be additional attempts to examine the relationship of this principle to organic evolution, and since many readers may wish an introduction to the subject, Chapter III is devoted to its application to chemical reactions; the kind of application that needs to be made to living organisms as well.

In Chapter III, and from time to time thereafter, I shall resort to the use of analogies and models, with the hope of simplifying certain concepts for the uninitiated, or where physical knowledge is inadequate for a complete description of living systems. In formulating such models, I shall try to keep in mind a statement I once heard made by the physiologist Sir Archibald Vivian Hill, to the effect that one should not construct a model too near to reality, lest he mistake the model for

the thing itself. However well I may follow this astute advice, I trust the reader himself will have no difficulty in distinguishing between the model and the real. I shall attempt to choose the models so that the nonspecialist will not be grossly misled, but may be able to gain a reasonable impression of the "forest" without being confused by the "trees." The sophisticate will, of course, recognize the weaknesses, and know how to overlook them while giving his attention to the general argument.[1]

Many things treated in this book have implications within that fascinating terrain where biology and philosophy meet. Indeed, such things alone can make such a treatment worth the undertaking. It seems better, though, to bring them together in the final chapter after the argument has been presented, rather than to anticipate at this point.

[1] But am I too sanguine here, and may not my analogies and models rise up to haunt me ever after?

II · THE CHRONOLOGY OF EVOLUTION

"Ce qui est admirable, ce n'est pas que le champ des étoiles soit si vaste, c'est que l'homme l'ait mesuré."—ANATOLE FRANCE

THE dating of evolutionary events is based on the reasonable postulate that the existing sedimentary rocks of the earth's surface were formed in layers, one after the other. They were formed in different ways, however, and their relationships have been disturbed by various changes, some catastrophic, some gradual. Hence, their relative positions often fail directly to reveal their chronological order. The arrangement of these layers according to a logical time sequence has called for fine detective skill as well as laborious investigation on the part of geologists and paleontologists examining the composition, structure, and fossil content of the rocks as well as their relative positions. This arrangement of the rocks according to their order in time —which provides an outline of evolutionary events—was possible without any definite measure of the lengths of time involved in forming the various layers. Indeed, the basic features of this outline were established long before an accurate method of timing was available. Early estimates of the relative time elapsed in the building of given formations, as compared to others, have proven quite accurate in many cases; but early estimates of absolute time were ridiculously short compared to the values that are now accepted.

Whereas early estimates placed the age of the earth at fifty to one hundred million years or even less, the newer chronology, based upon the "radioactive" method, shows some of the rocks of the earth's crust to be at least as old as four billion years.[1] The age of the earth is now thought to be nearly five billion years. The recognition of this vast

[1] The term *billion* used in this book is the "American" billion, 1,000,000,000 = 10^9.

stretch of time available for evolution makes a great difference in the perspective with which this process may be viewed. Much more ample time is allowed for the achievement of given steps than could have been imagined in Darwin's time, or even until very recently.

The radioactive method for determining the age of rocks takes advantage of certain nuclear reactions; for example, the formation of lead from uranium by radioactive disintegration,

$$_{92}U^{238} \rightarrow {}_{82}Pb^{206} + 8{}_{2}He^{4} + 6{}_{-1}e^{0} \qquad \text{(II-1)}$$

This is a nuclear reaction and is not to be confused with chemical reactions of the usual type, which are treated in the next chapter. It may be read: one atom of uranium 238 goes to one atom of lead 206, eight atoms of helium, and six electrons. The symbols, U, Pb, and He, indicate the chemical species, and the subscripts to the left are the atomic numbers. All atoms having the same atomic number, which represents the number of charges on the nucleus of the atom, have the same chemical properties, so their presence in the above equation is redundant since the symbol for the element says the same thing. There will be more to say about atomic numbers in Chapter VI, but for the present the superscripts to the right of the chemical symbols focus our attention. These are the *mass numbers* (for most practical purposes equal to the atomic weights), which indicate in the above equation that only one isotope of the particular chemical species is concerned. Isotopes are elements having the same atomic number and, hence, the same chemical properties, but different mass numbers and molecular weights. The symbol $_{-1}e^{0}$ represents the electron, which has a single negative charge and zero mass number.

Lead may also be formed from uranium by the reaction

$$U^{235} \rightarrow Pb^{207} + 7He^{4} + 4e^{0} \qquad \text{(II-2)}$$

but different isotopes are involved. Lead is also formed from thorium

$$Th^{232} \rightarrow Pb^{208} + 6He^{4} + 4e^{0} \qquad \text{(II-3)}$$

The isotopes Pb^{206}, Pb^{207}, and Pb^{208} constitute what is known as "radiogenic" lead. Another isotope Pb^{204} present in small quantities in some rocks is called "non-radiogenic" lead because it is not formed by any radioactive process.

The above reactions (II-1, 2, 3) take place at very low rates, which have been accurately determined by the rate of ejection of electrons. For example, the time required for half of a given quantity of pure uranium 238 to change to lead 206 is 4,560 million years. Knowing these rates of radioactive decay, the minimum age of a given rock may

be determinable from the quantities of the various isotopes present. Some of the isotopic measurements are more reliable than others; the best methods may serve as checks against each other in some cases. The earliest determinations by the radioactive method were based on what amounted to the assumption that only reaction II-1 took place. The introduction of isotopic analysis and the continual perfection of methods have made revision of age estimates necessary from time to time, but there has never been any question that the age of the oldest rocks are to be reckoned in billions of years.

Other radioactive methods have yielded results which are in general agreement with those involving determinations of lead. Helium is formed in the above reactions and its measurement has also been employed, but being a gas, it is likely to escape from the rocks, and this has introduced uncertainty into the application of this method. It has been applied with success, however, to iron meteorites, which have been assigned an age close to that estimated for the earth's crust. Quite recently another nuclear reaction has been successfully employed, the decay of the element rubidium to strontium.

$$_{37}Rb^{87} \rightarrow {}_{38}Sr^{87} + {}_{-1}e^{0} \qquad \text{(II-4)}$$

These different methods yield somewhat different estimates of the ages of various rocks, but on the whole they are in good agreement.

Within recent years the dates of the earlier rocks have been generally pushed backwards, as the result of new methods and more critical application of older ones. It seems not unlikely that some of the present values may be increased still further. These changes have not decreased confidence in radioactive dating, but have called for more tentative acceptance of dates until further study brings general agreement.

The newer values for the age of the earliest rocks indicate the earth to have been in existence well over the three billion years that was generally accepted a few years ago for the age of the universe. That figure, which must now be regarded as a rough approximation, was based on the apparent rate of expansion of the universe. It is generally agreed on the basis of such estimates that the universe is not over a few billion years old. The concept of the expanding universe has itself been challenged, however, and it seems we shall have to wait for explanation of these and other discrepancies until cosmological theories become stabilized. The problems dealt with in this book are little affected by events outside our solar system and its evolution, so that the above and other cosmological uncertainties need not be of direct concern.

The story of the earth during the past few billion years is to be sought principally in its surface rocks. At some early date the earth's

surface was divided into areas of dry land and areas of ocean. It is probable that the areas and outlines of the continental masses have been for a very long time much the same as at present, although the exact size and shape of the dry land area has changed with periods of elevation and submergence of portions of these masses. During periods of submergence, layers of sedimentary rocks were formed, only to be folded and broken during later periods of adjustment of the earth's crust. Intrusion of molten material from deeper layers of the earth into and onto the surface has brought about the metamorphosis of sedimentary rocks as well as the formation of other types. Erosion of the surface by water, and lesser factors such as wind and glaciation, have sculptured the uplifted mountain masses, creating the landscapes characteristic of various geological periods. These processes will be discussed in a little more detail in Chapter V.

For the moment it is enough to say that the traces left by surface changes recurring in a more or less cyclical fashion permit the recognition and dating of events, which in sum constitute the history of the earth's crust before the appearance of a reasonably continuous fossil record. From the beginning of the fossil record we have a powerful tool for unraveling geological history, as well as a record of the evolution of living things themselves. This continuous record begins about half a billion years ago, although there are "sporadic" occurrences of fossils in rocks that go back a few billion years farther. Presumably the first living organisms possessed no hard parts, were too small, or were devoid of other characteristics which might have permitted them to leave their imprints in the rocks, so it must be assumed that the origin of life is hidden somewhere beyond the beginning of the fossil record. Life's exact moment of appearance is a matter of the vaguest speculation, and it may be best to think of this event as having occurred sometime about three billion years ago, but probably spread over a goodly period without being sharply definable.

There are so many uncertainties regarding geological events and the fossil record that it would probably be impossible to outline them to everyone's satisfaction, even in the most general terms. But some such outline is needed if we are to approach the evolutionary problem at all, and Figure 1 is introduced for the purpose. This diagram represents the Geological Time Scale, and the order of certain major occurrences in the fossil record and evolutionary history. The dates may be taken as reasonable approximations, in agreement with currently accepted ideas of geological chronology. They may be subject to revision, and it is to be expected that revision will generally be in the direction of greater age, since dating by the radioactive method gives minimum rather than maximum values. Various systems of nomen-